REPORT OF THE DARK ENERGY TASK FORCE

Albrecht et al.

A summary and comparison on different techniques to explore dark energy.

The goals for a properly executed dark energy program:

1. Whether accelerating expansion is consistent with a cosmological constant.

2. Evolution of dark energy

3. Search for possible failure of GR

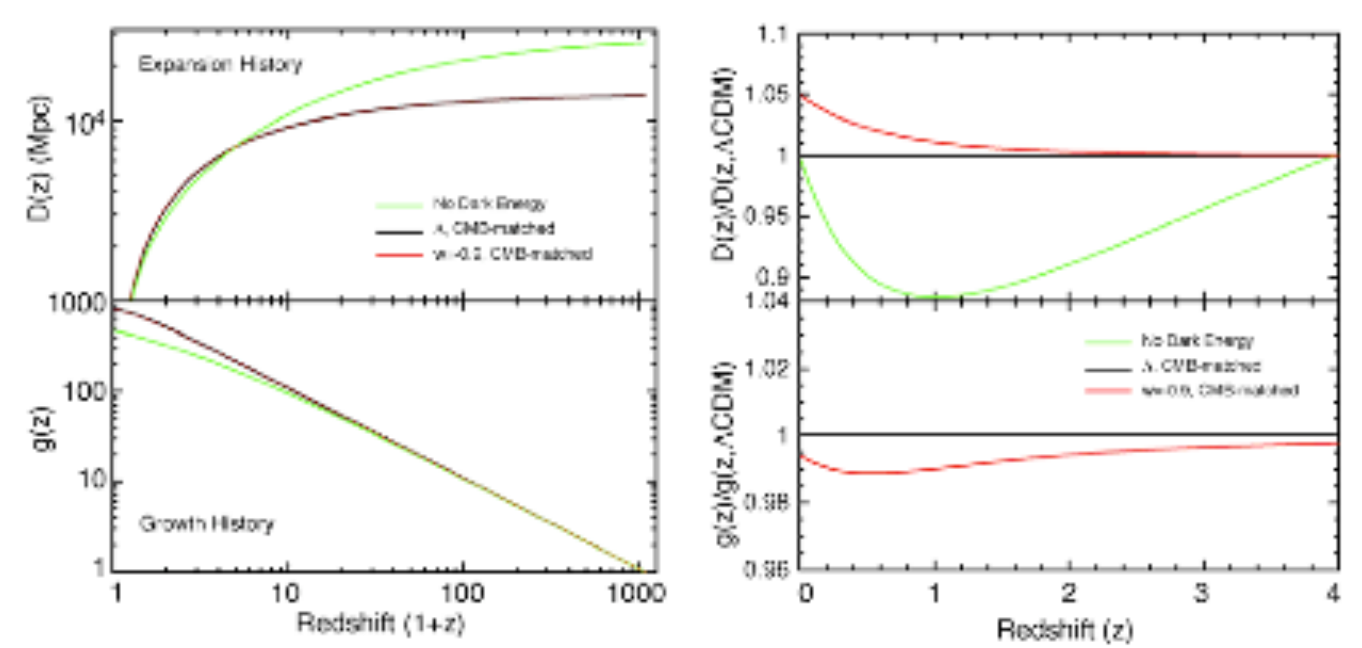
observables

measurable	Definition
proper distance	$D(z) = \int_0^z \frac{dz'}{H(z')} = \begin{cases} \lvert k\rvert^{-1/2} \sin^{-1}\left[\lvert k\rvert^{1/2} r(z)\right] & k>0 \\ r(z) & k=0 \\ \lvert k\rvert^{-1/2} \sinh^{-1}\left[\lvert k\rvert^{1/2} r(z)\right] & k<0 \end{cases}$
luminosity distance	$d_L(z) = r(z)(1+z)$
angular diameter distance	$d_A(z) = r(z)/(1+z)$
volume element	$dV = \frac{r^2(z)}{\sqrt{1-kr^2(z)}} dr\, d\Omega$

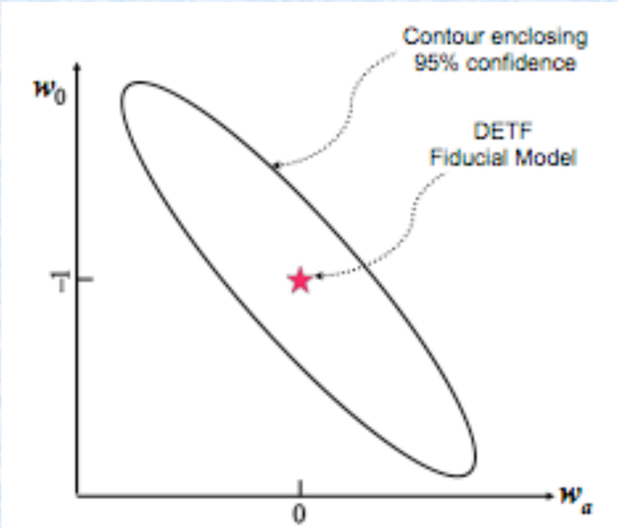
growth of structure

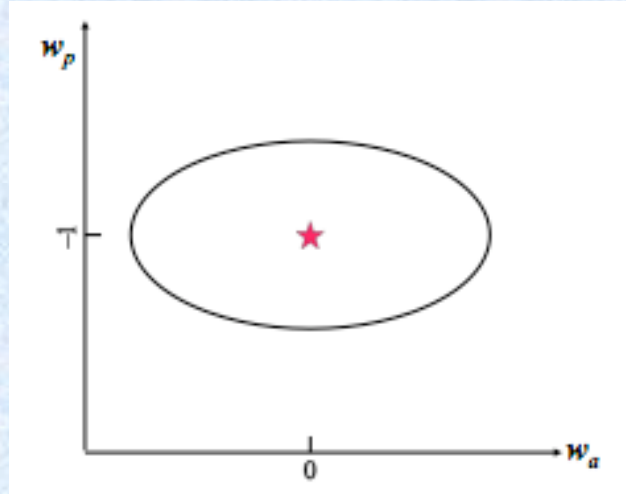
$$\ddot{g} + 2H\dot{g} = 4\pi G\rho_m g = \frac{3\Omega_m H_0^2}{2a^3} g\,.$$

Fig. VI-2: The primary observables for dark-energy – the distance-redshift relation D(z) and the growth-redshift relation g(z) – are plotted vs. redshift for three cosmological models. The green curve is an open-Universe model with no dark energy at all. The black curve is the "concordance" ΛCDM model, which is flat and has a cosmological constant, i.e., $w = -1$. This model is consistent with all reliable present-day data. The red curve is a dark-energy model with $w = -0.9$, for which other parameters have been adjusted to match WMAP data. At left one sees that dark-energy models are easily distinguished from non-dark-energy models. At right, we plot the ratios of each model to the ΛCDM model, and it is apparent that distinguishing the $w = -0.9$ model from ΛCDM requires percent-level precision on the diagnostic quantities.



Dark Energy Figure of Merit





$$w = w_0 + w_a\,(1\text{-}a)$$

$$w_p = w_0 + (1 - a_p) w_a,$$

Figure of Merit (FoM):
1 / (area of 95% contour)
in w_0, w_a plane
same as in w_p, w_a plane

combining techniques can
lead to large increases in FoM

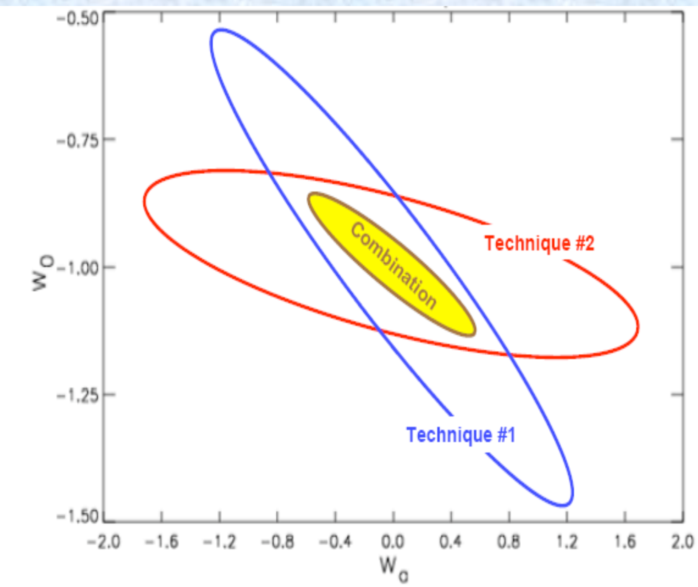


Illustration of the power of combining techniques. Technique #1 and Technique #2 have roughly equal DETF figure of merit. When results are combined, the DETF figure of merit is substantially improved.

Model advances in DE science in stages:

I: represent what is now known.

II: represent the anticipated state of knowledge upon completion of ongoing DE projects.

III: comprises near-term, medium-cost, currently proposed projects – aim for a factor of 3 increase in FoM

IV: comprises a Large Survey Telescope (LST), and/or the Square Kilometer Array (SKA), and/or a Joint Dark Energy (Space) Mission (JDEM). – aim for a factor of 10 increase in FoM (relative to stage II)

Findings of DETF (Four important techniques):

1. Baryon Acoustic Oscillations (BAO)
2. Galaxy Cluster (CL)
3. Supernova (SN)
4. Weak Lensing (WL)

They have different strengths and weaknesses and are sensitive in different ways to DE properties and other parameters.

Each technique can be pursued by multiple observational approaches.

Supernovae

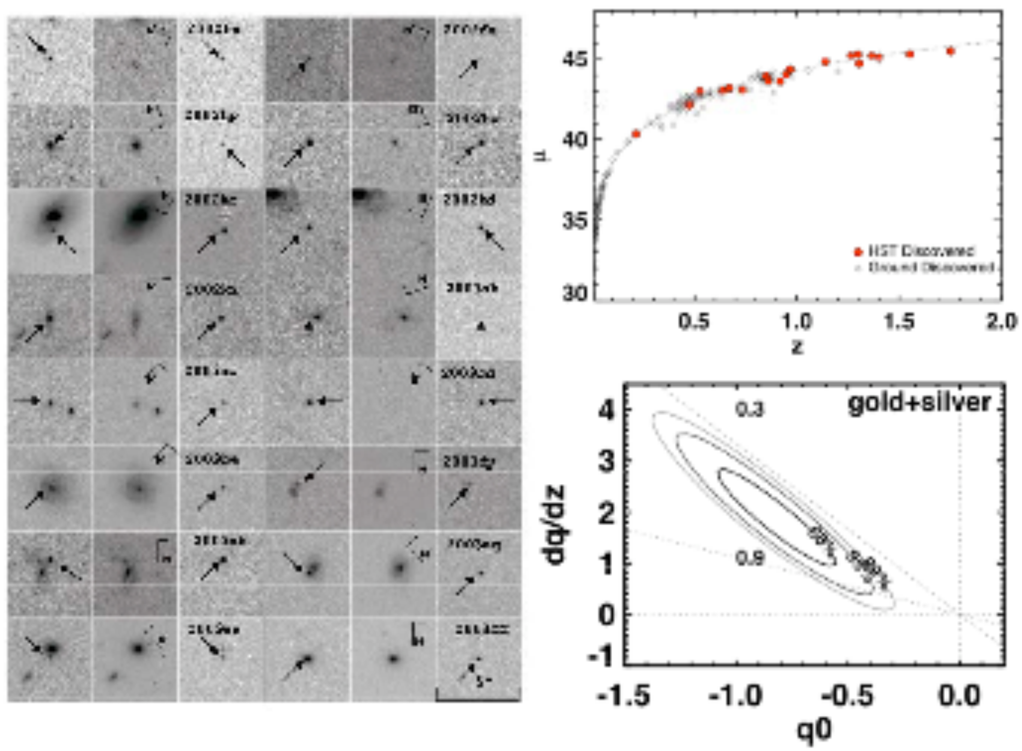


Fig VI-3: Left: High-redshift supernovae observed from HST by Riess et al (2004). Right: Cosmological results from the GOODS SNe (Riess et al. 2004). Upper panel: distance ($\mu = 5 \log_{10} d_L + \text{const.}$*) vs. redshift; lower: constraints on present-day acceleration.*

Supernova (SN) :

Strengths: The most established method and the one that currently contributes the most to the constraint of dark energy.

Weaknesses: Bias dark energy parameters

LST: Large numbers of high signal-to-noise events, improve supernovae as standard candles and control evolutionary effects

Space Mission: Unified, stable photometric calibration

SKA: None

The levels of maturity: Most powerful and best proven technique for studying DM.

Improvement: Detailed spectroscopic and photometric observations

Baryon Acoustic Oscillations

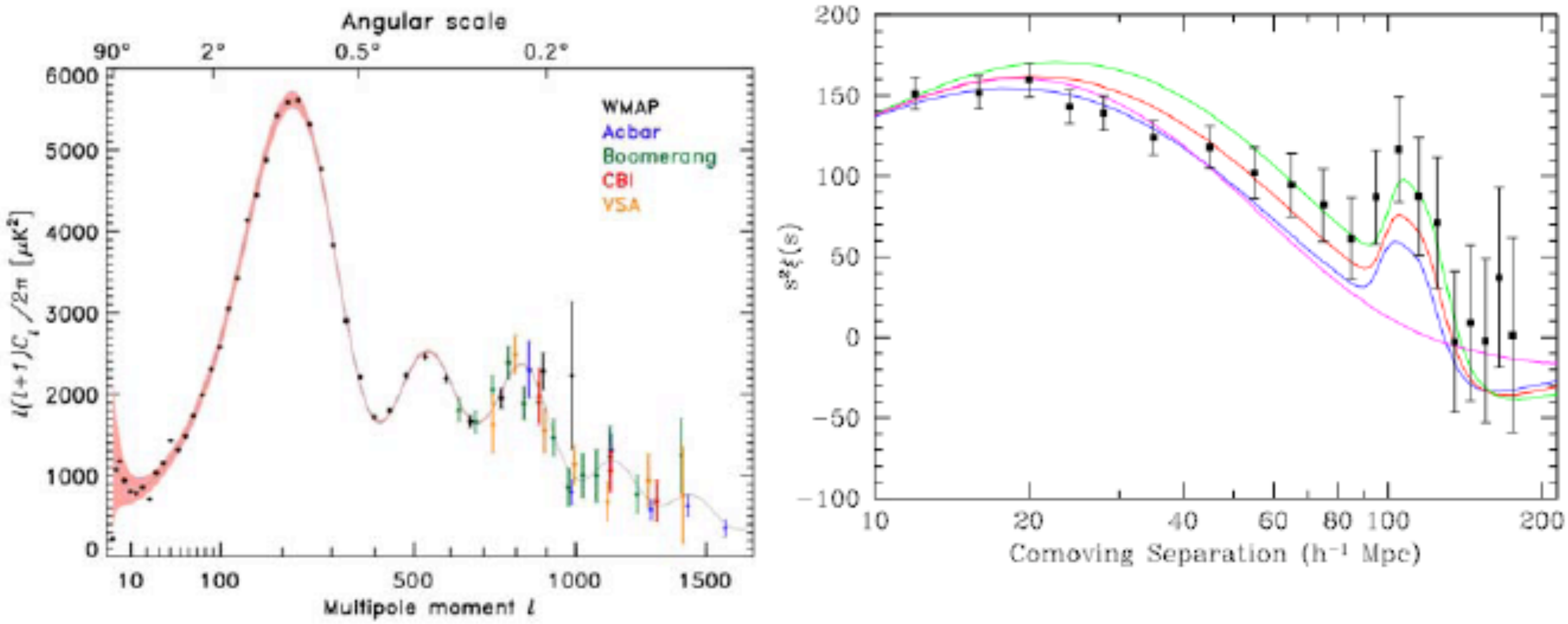


Fig. VI-4: The baryon acoustic oscillations are seen as wiggles in the power spectrum of the CMB (left, Hinshaw et al. 2003), and have now been detected as a feature in the correlation function of nearby galaxies using the Sloan Digital Sky Survey (right, Eisenstein et al 2005).

Baryon Acoustic Oscillation:

Strengths: least affected by systematic uncertainties.

Weaknesses: least statistical power

LST: A survey that foregoes spectroscopy can largely compensate for the increased statistical errors by covering very large amounts of sky.

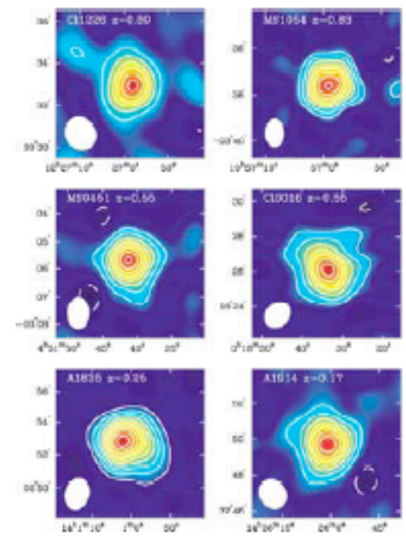
SKA: High-precision redshifts without additional effort.

Space Mission: More quickly than ground-based surveys

Maturity: New, less affected by astrophysical uncertainties.

Improvement: Better understanding on theoretical side

Galaxy Cluster Counting



1. Comoving volume element depends on expansion history

2. Mass function sensitive to density fluctuations

Galaxy Cluster Counting (CL) :

Strengths: Sensitive to both the expansion and growth histories of the Universe.

Weaknesses: Very sensitive to errors in “mass-observable” relations, least reliable.

LST: Deep weak-lensing observations would calibrate the mass-observable relation for optical (LST) observables.

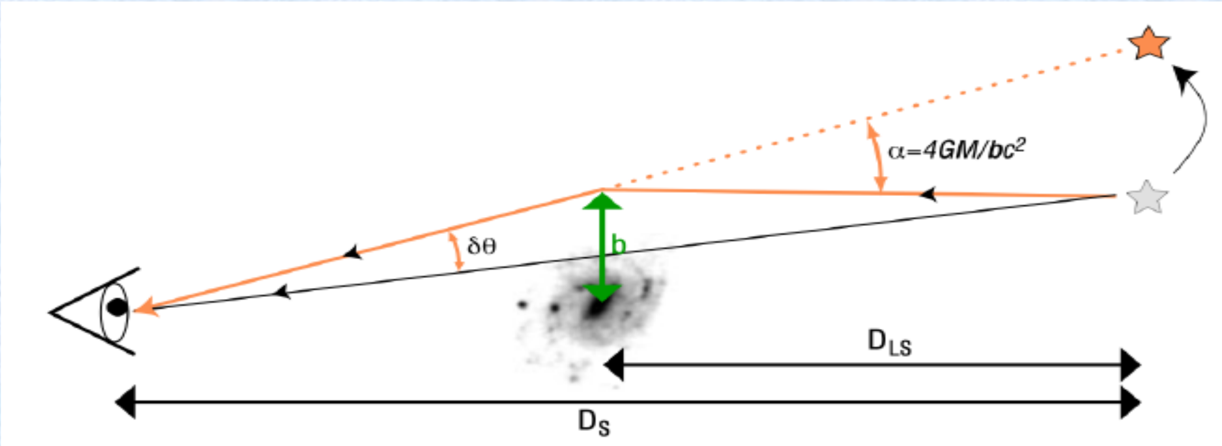
Space Mission: Benefit from in the same way as WL surveys do, by offering lower noise levels for WL mapping.

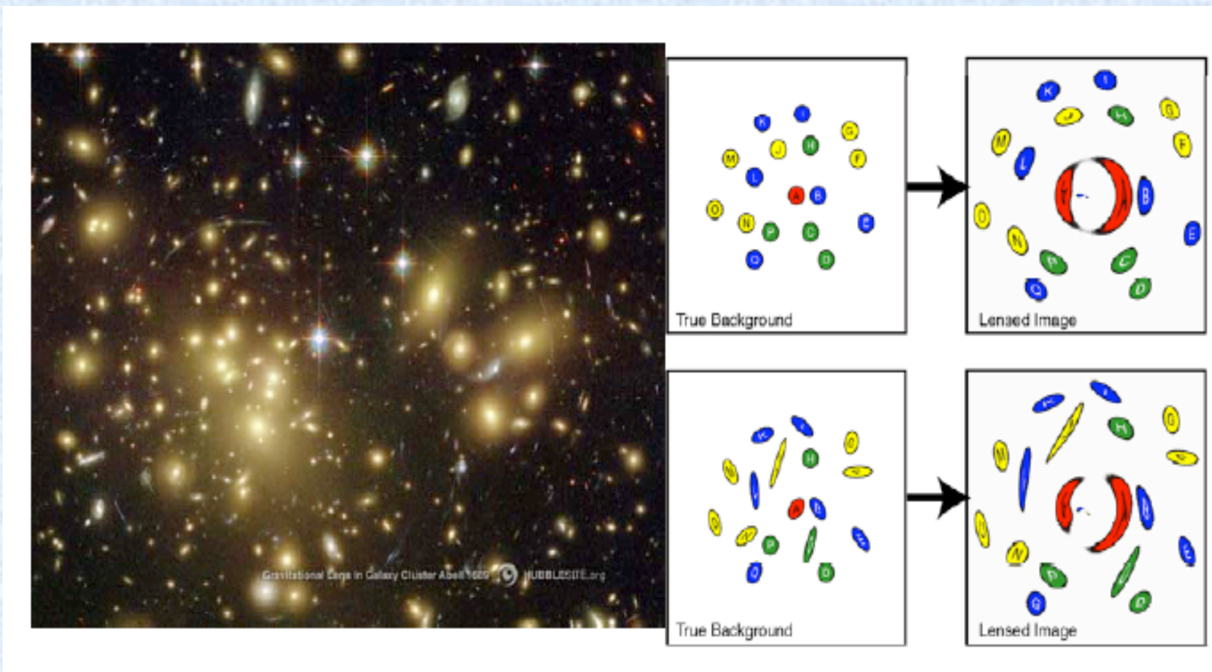
SKA: None

Maturity: Good statistical potential, largest systematic errors

Improvement: Better constrains to relationship between galaxy cluster mass and observables.

Weak Gravitational Lensing





Similar as cluster counting, probe DE via both:

expansion history;

growth history of fluctuations.

Weak Gravitational Lensing (WL):

Strengths: Greatest potential, multitude of WL statistics, Both expansion and growth history may be determined from WL data.

Weaknesses: Systematic errors arising from incomplete knowledge of the error distributions of photometric redshifts

LST: Rapid; Reducing statistical errors; Enabling repeated observations.

Space Mission: Improve photo-*z* accuracy and reliability, and extend the galaxy sample to higher redshifts.

SKA: Precise redshift information for every detected galaxy

Maturity: New, systematic errors

Improvement: Calibrate the photometric redshift technique

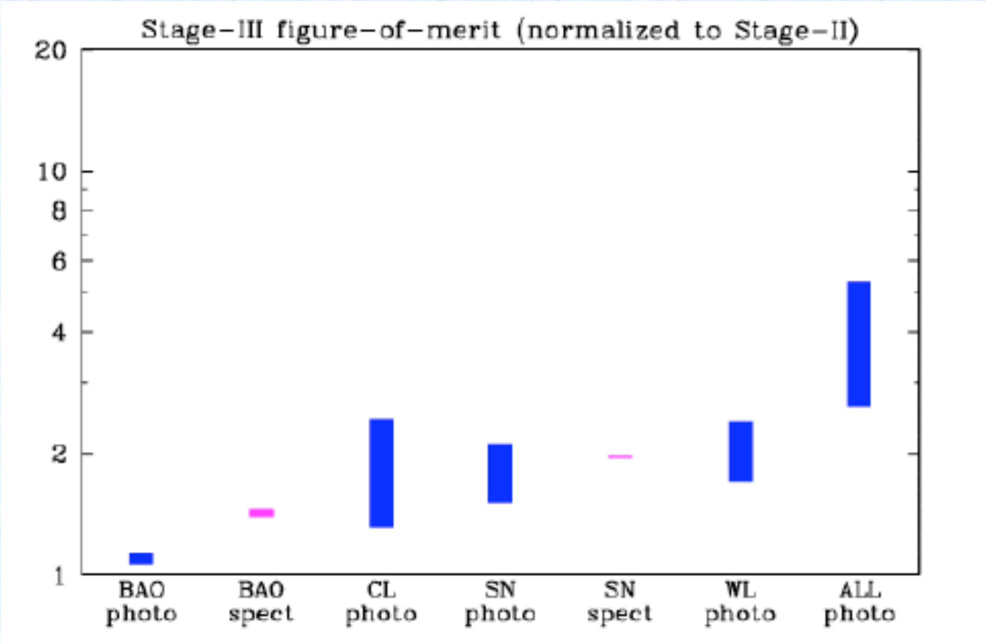
Six types of near-term, medium-cost, currently proposed (Stage III)projects have been considered:

BAO photo, BAO spect, CL photo,

SN photo, SN spect, WL photo.

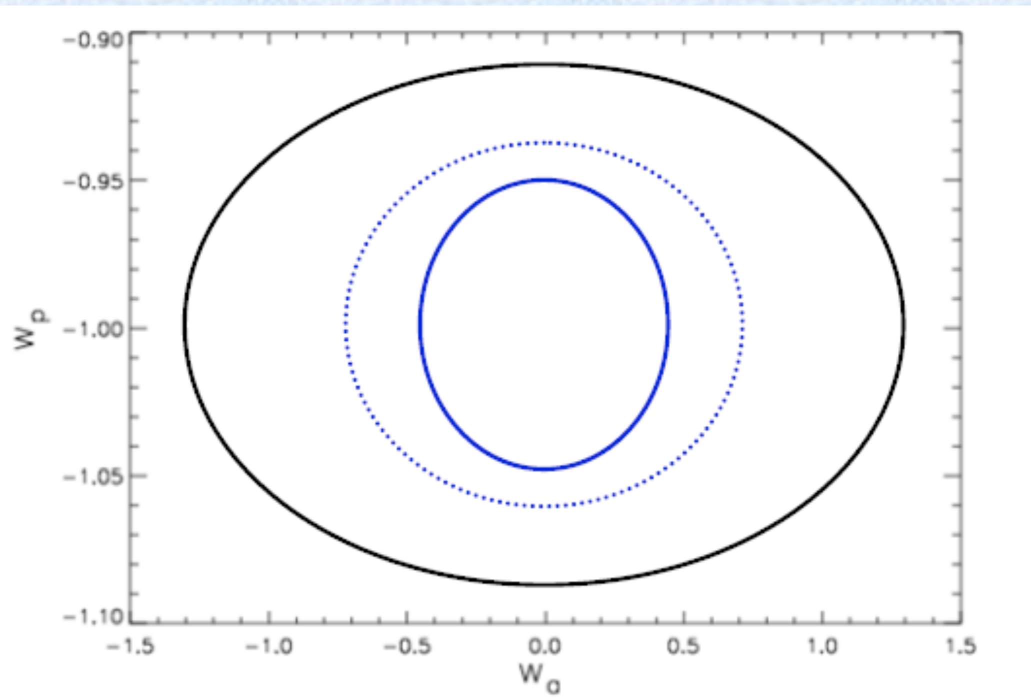
Cost in the range of tens of millions of dollars.

Benefits: Better understanding on DE parameters and improvements in the DETF figure of merit.



Potential improvement

Each bar extends from pessimistic systematics to optimistic systematics



The outer contour is for Stage II,

Inner contour is for pessimistic and optimistic case.

Four types of Stage- IV projects:

Optical Large Survey Telescope (LST)

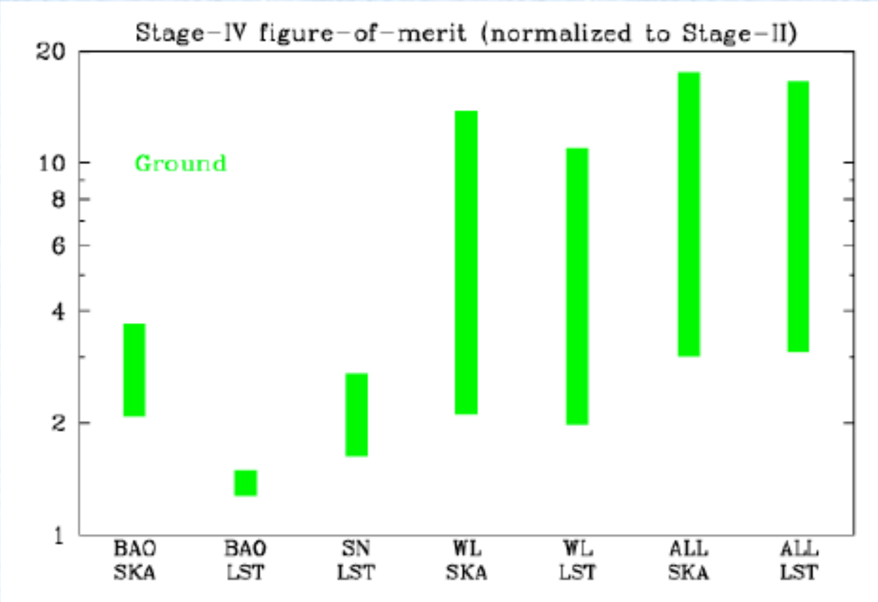
Optical/NIR Joint Dark Energy Mission (JDEM) satellite

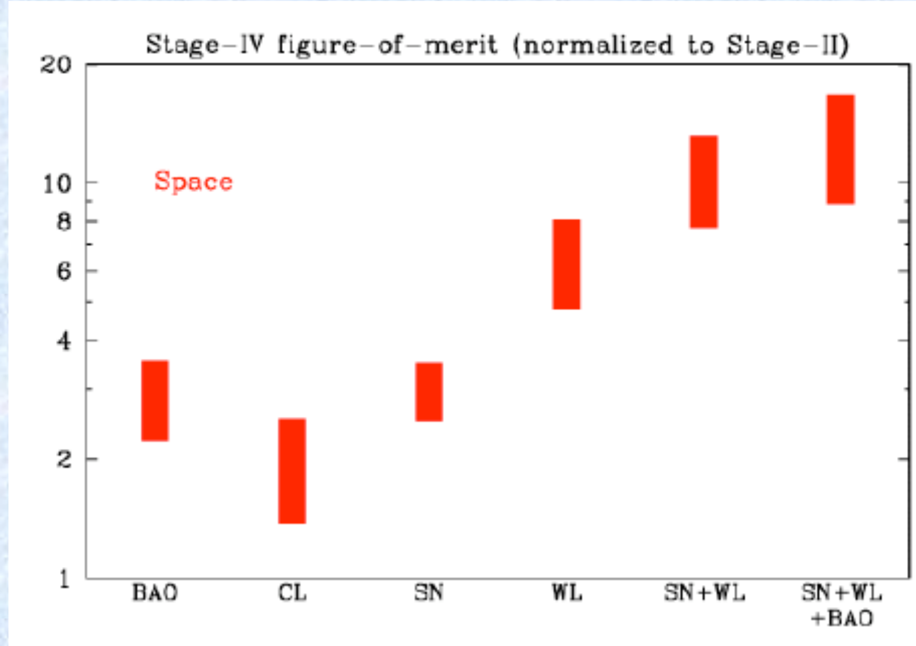
X-ray JDEM satellite

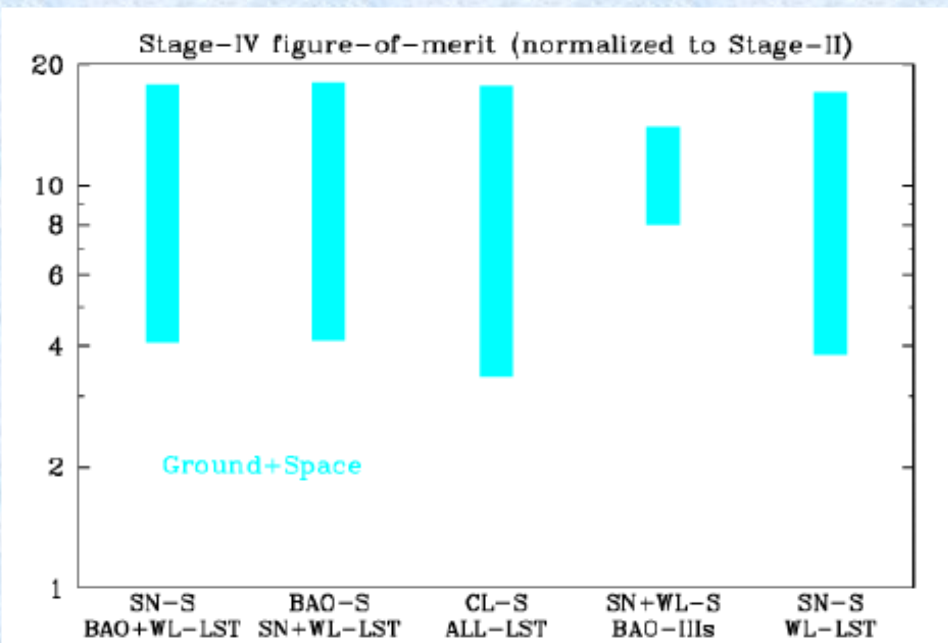
radio Square Kilometer Array (SKA)

Cost: $ 0.3 – 1 B range each

A mix of techniques is essential for a fully effective Stage-IV program. (ground-based program, space-based program)







Potential improvement in FoM, from pessimistic to optimistic.

Stage III:

- Dark Energy Survey (DES)
- Hobby-Eberly Telescope Dark Energy Experiment (HETDEX)
- Wide-Field Multi-Object Spectrograph (WFMOS)
- Pan-STARRS-4, a large optical/near-IR survey telescope
- etc…

Stage IV:

a. Large Synoptic Survey Telescope (LSST)

b. Joint Dark Energy Mission (JDEM)

   i. Dark Energy Space Telescope (DESTINY)

   ii. Joint Efficient Dark-energy Investigation (JEDI)

   iii. Supernova Acceleration Probe (SNAP)

c. Square Kilometer Array (SKA)

d. Cluster Surveys:

   i. The 10K X-Ray Cluster Survey

   ii. NASA Medium-Explorer Mission

   iii. Constellation-X

e. Other Projects:

i. The Giant Segmented Mirror Telescope (GSMT)

ii. James Webb Space Telescope (JWST)